AFRL-SN-RS-TR-2002-56
Final Technical Report
April 2002

ROTHR MODE-LINKING USING NEURAL NETWORKS

Riverside Research Institute

APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

AIR FORCE RESEARCH LABORATORY
SENSORS DIRECTORATE
ROME RESEARCH SITE
ROME, NEW YORK

This report has been reviewed by the Air Force Research Laboratory, Information Directorate, Public Affairs Office (IFOIPA) and is releasable to the National Technical Information Service (NTIS). At NTIS it will be releasable to the general public, including foreign nations.

AFRL-IF-RS-TR-2002-56 has been reviewed and is approved for publication.

APPROVED: ROBERT DENTON
Project Engineer

FOR THE DIRECTOR: ROBERT G. POLCE, Chief
Rome Operations Office
Sensors Directorate

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	Apr 02	Final Jul 95 - Dec 96

4. TITLE AND SUBTITLE
ROTHR MODE-LINKING USING NEURAL NETWORKS

5. FUNDING NUMBERS
C - F30602-95-C-0211
PE - 63790D
PR - H236
TA - 00
WU - R3

6. AUTHOR(S)
R.L. Friedman, W.P. Gnadt

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Riverside Research Institute
Boston Research Office
70 Westview St
Lexington MA 02173

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory/SNRD
26 Electronic Pky
Rome NY 13441-4514

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
AFRL-SN-RS-TR-2002-56

11. SUPPLEMENTARY NOTES

Air Force Research Laboratory Research Proect Engineer: Robert Denton, SNRD, 315-330-7067

12a. DISTRIBUTION AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*
A novel concept using neural network technology was employed to find the correct linkage of ionospheic modes in a multi-mode multi-target environment given a model of the ionosphere. The technology employed consists of a self-organizing feature map (SOFM) to provide separation of multiple targets containing multiple modes followed by an Adaptive Resonance Theory Map (ARTMAP) to perform spatial pattern recognition of ionospheric mode patterns and to link them to a single ground range. The ARTMAP recognition system is trained on the Coordinate Registration (CR) tables produced by ROTHR. The current CR tables are updated every 12 minutes, thus providing a real-time assessment of the ionosphere. The exactness of the mode-linking procedure consequently depends on the accuracy of the Coordinate Registration tables.

14. SUBJECT TERMS	15. NUMBER OF PAGES
OTH Radar, Propagation	24
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

INTRODUCTION

The organization of this report will familiarize the reader with coordinate registration basics. The concept of transforming from radar slant range to ground range is examined and developed. The concept of ray-tracing is presented onl y briefly to provide the reader with a departure point to further understanding. Finally, the concept of ROTHR "slant tracks" and the structure and techniques employed for the current ROTHR mode-linker are provided. The sections introducing the neural technology draw on material from the background sections to describe the techniques of applying neural networks to this problem.

BACKGROUND

The general problem of combining different ionospheric modes of targets at long distances using OTH radar is not new. However, the ROTHR system (A/N TPN-71) performs this function in real-time. ROTHR performs well at this task and supported end-user community in a highly effective manner.

Recently, computational advances have allowed the application of advanced algorithms to a real-time environment. We first consider the general problem of performing classification in a multi-target radar environment given the multiplicity of ionospheric modes which are returned via radar backscatter. The origin of such modes is from ionospheric layers with different ionospheric heights of maximum ionization.

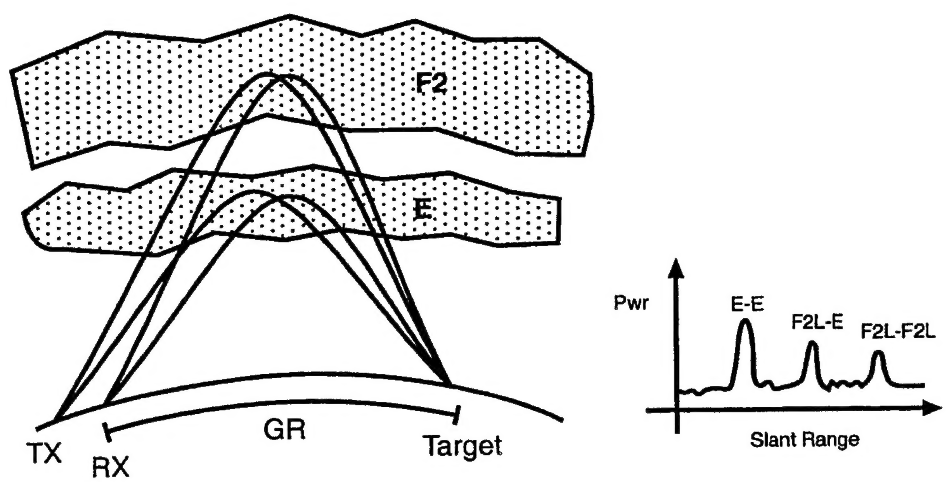


Figure 1. Ionospheric Single Target Multi-Mode Ray Geometry

The example appearing in Figure 1 depicts an OTH radar propagating electomagnetic energy, confined spectrally from 5 to 28 MHz, out from the transmit site (labeled TX).

This energy is refracted from both the E and F_2 ionospheric layers, then backscattered from a target at a distance GR away in ground range, and received at the receiving array. A multiplicity of modes now presents itself for the isolated target at ground range, GR. These two-way modes are as follows:

Table 1. Bistatic 3-Layer Mode Combinations

back / out	E	F_2L	F_2H
E	E-E	E-F_2L	E-F_2H
F_2L	F_2L-E	F_2L-F_2L	F_2L-F_2H
F_2H	F_2H-E	F_2H-F_2L	F_2H-F_2H

where the nomenclature employs "L" for the low angle, "H" for the high angle, and the grouping consists of elements of the ray-out and ray-back components.

Hence, in general, the nomenclature, in Table 1., may be interpreted as the following:

(Ray out from TX to target) - (Ray back to RX from target)

and since the ROTHR bistatic separation is 131.5 km (~70 nmi) between TX and RX, we may consider combinations of "out" and "back" modes reciprocal since,

$$\|Tx - Rx\|_{GroundRange} \ll GR \qquad \textbf{Equation 1}$$

This inequality translates to a factor of twenty five at 1800 nmi. For the purposes of this report we have assumed Equation 1 is valid.

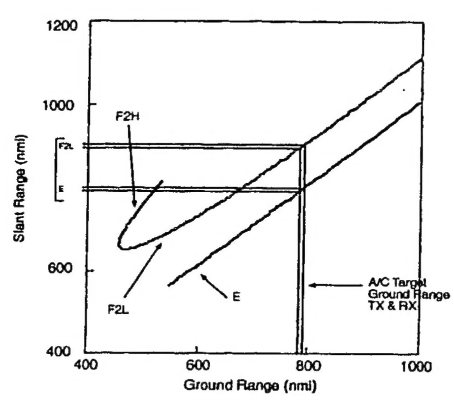


Figure 2. Error Due To Bistatic Separation Of The Transmit And Receive Site

However, ROTHR Real-Time Ray Trace (RTRT) improvements may reduce the validity of this assumption and require a more accurate bistatic computation. This will increase the mode-linking burden for both ROTHR linkage software and for alternative techniques, such as those investigated by this report. One advantage of the approach developed here is the reduced computational requirements compared with the current mode-linking approach. This is true whether the selected computing platform is serial or parallel in architecture.

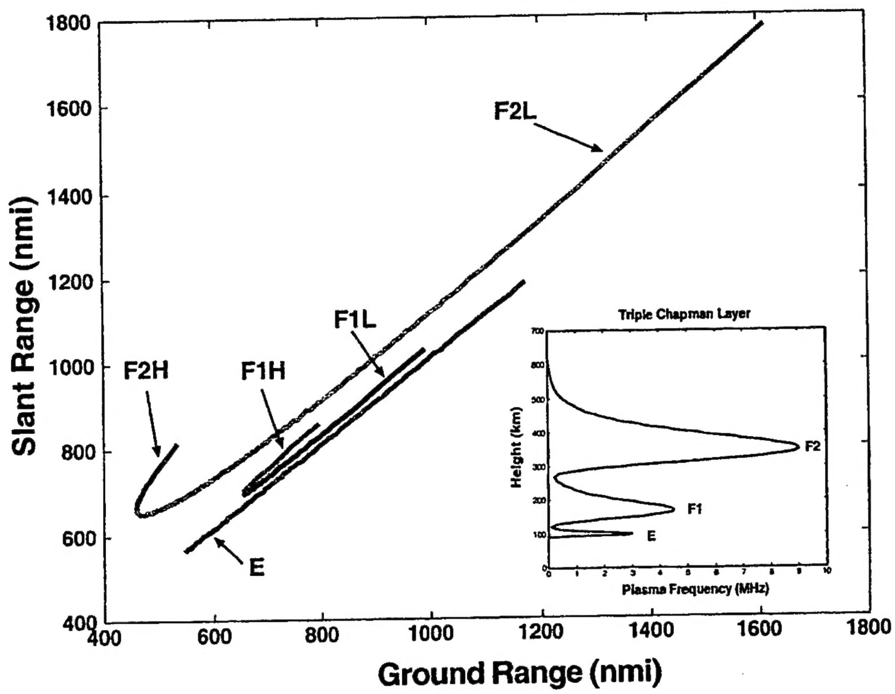


Figure 3. Ray-Tracing Using Triple Chapman Ionospheric Layers

Figure 3 provides some additional insight into the nature of ray refraction for an electron density model ("ionospheric model") which consists of three Chapman layers summed together as follows:

$$f_n^2(h) = \sum_{i=1}^{i=3} f_{c_i}^2 \exp\left\{\frac{1}{2}(1-\xi-e^{-\xi})\right\} \qquad \textbf{Equation 2}$$

where the reduced height $\xi(h)$ is given in terms of the true height by the equation,

$$\xi(h) = \frac{(h-h_m)}{h_s} \qquad \textbf{Equation 3}$$

where the parameters of Equation 2 and Equation 3 are the layer critical frequency f_c, the height of maximum electron density h_m, and the layer scale height h_s. Summing three chapman layers provides a 9-parameter model for a one dimensional ionosphere. Variation of these parameters forms sets of ionospheric models characterizing the state of the ionosphere for a given instant in time.

IONOSPHERIC RAY TRACING

The relationship between radar slant range[1] and target ground is accomplished by ionospheric ray-tracing through the plasma as specified by Equation 2. Ray-tracing through the Triple Chapman electron density profile provides ray paths to the ground as a function of frequency. These curves define the slant range to ground range conversion for a particular ionospheric model. Such ray-traced curves provide the basis for the Coordinate Registration tables used by the ROTHR mode linker portion of the tracker sub-system to determine whether a given set of slant tracks is originating from a single ground target.

To form a coordinate registration table, we first combine the one-way ray paths to form a round-trip set including all the layer mode combinations. This process is performed based on ROTHR's assessment of the "state" of the ionosphere for a Propagation Management and Assessment (PMA) cycle nearest the time of the dwell. The PMA software chooses a model for the ionosphere which produces a set of ray-tracings. These ray-tracings vary as a function of ionospheric frequency, since the electron density profile must be used in conjunction with the index of refraction to determine the ray curvature as a function of height. The expression for the ionospheric index of refraction, in the absence of the Earth's magnetic field is[2],

$$\mu(h, f) = \left(1 - \left(\frac{f_n^2(h)}{f_{op}^2}\right)\right) \qquad \textbf{Equation 4}$$

which shows the dependence on the operating frequency, f_{op}, and the height of the ray, h. The operating frequency determines the range of rays to the target area. ROTHR routinely operators with Dwell Illumination Regions (DIR) of 500 nmi in depth and nominally 8 degrees wide[3]. These DIRs may be placed anywhere within ROTHR's coverage area, supportive of ionospheric propagation. Ionospheric coverage generally varies as a function of time of day, season of the year and sun-spot number.

DIR placement is radar operating frequency dependent. The ray-tracings of Figure 3 have been calculated for a fixed radar operating frequency. Consequently, in an operational sense, they would have been chosen for a specific DIR location. The following figure represents the set of round-trip paths for a fixed operating frequency and iono-

1. The term "slant range" is used here to refer to radar time delay converted to one-way range. The terminology used in the ionospheric literature employs the term "group path".
2. ROTHR's PMA architecture employs the Earth's magnetic field in its internal models. This simplified equation is designed to show the dependence on height and operating frequency.
3. However, there are combinations of waveform parameters which will produce other range depths at the expense of Doppler resolution.

spheric model. The separate rays are color-coded for ease of interpretation. The convention of denoting low-ray components with "L" and high ray components with "H" is also employed.

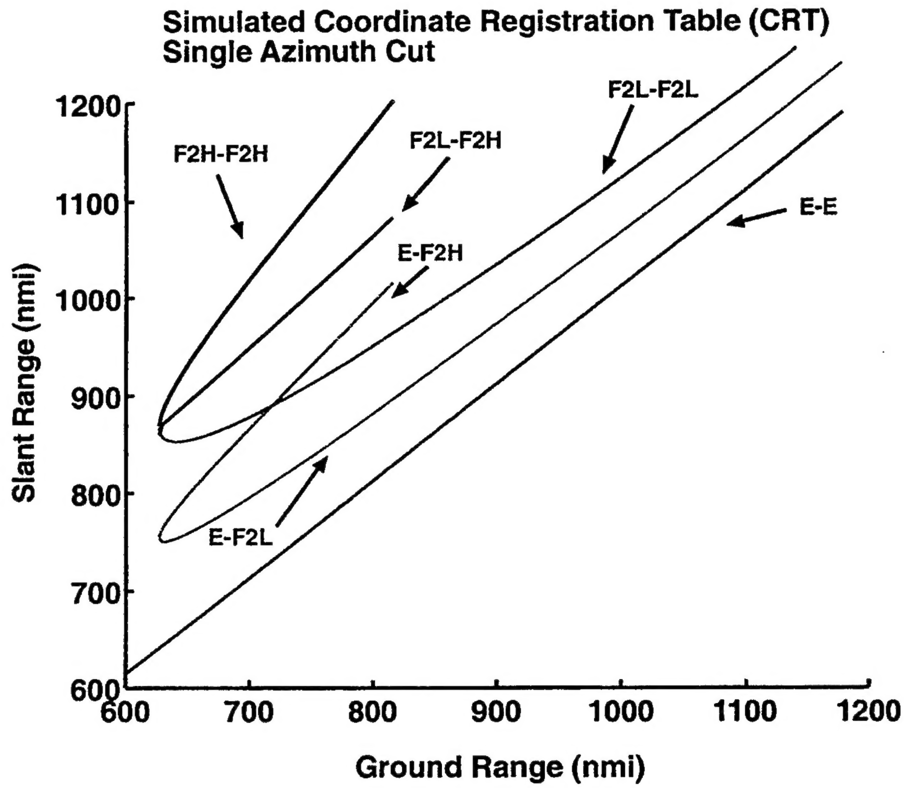


Figure 4. **Round-Trip Coordinate Registration Table (Single Azimuth)**

MAPS TO MULTI-MODE SLANT COODINATES FROM GROUND COORDINATES

The utility of this curve may be demonstrated by Figure 4. Consider the vertical cut through this figure as indicating a prospective target ground range. Possible ionospheric propagation modes for a given target ground range are then obtained by the intersecting curves of the ray-trace by scaling horizontal lines to the corresponding slant ranges. These returns are observed by the radar in slant track coordinates for the target at this ground range. The many-valuedness of this problem is readily apparent by these diagrams. The complexity is increased in a multi-target environment or if one considers the dynamics of the propagation medium. The ionosphere possesses many types of irregularities which will disturb propagation. These range from mild refractive irregularities to sun-spot driven black-outs (total absorption) and can nominally last between a few minutes and 30 minutes, respectively.

The number of curves intersected by the vertical cut at a fixed ground range determines the number of possible ionospheric modes which represent a single target at this particular ground range.

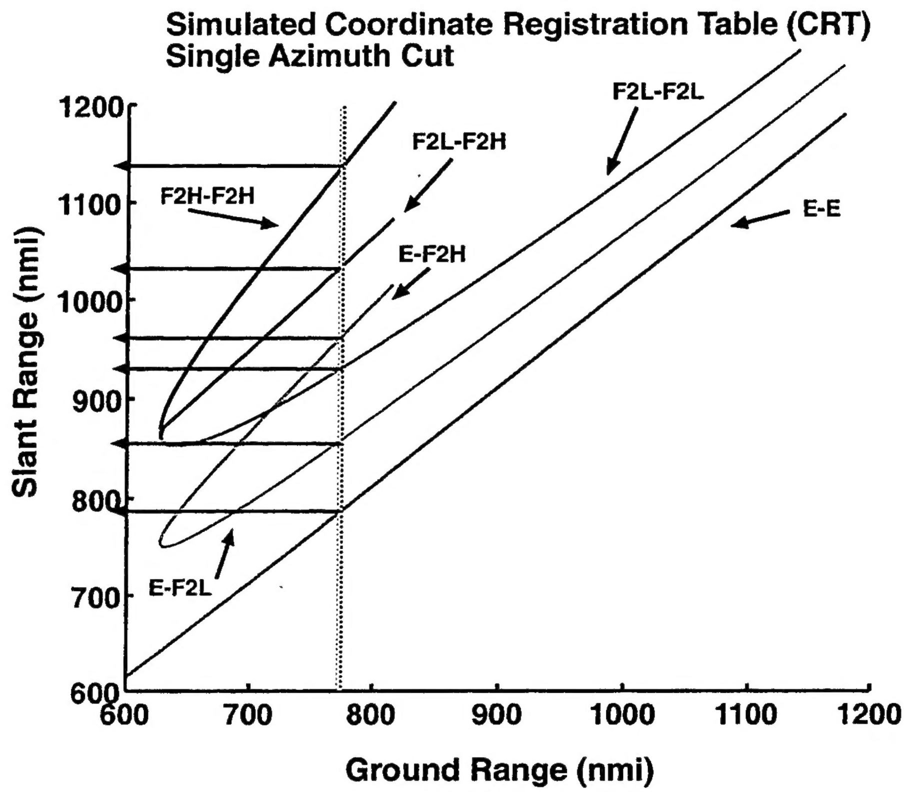


Figure 5. **Single Target Returns as a Function of Slant Range**

SLANT TRACKS

The problem of mode-linking is addressed at the output stage of the tracker. The tracker collects returned "peaks" from the Radar Post Processor and decides whether they associate with an existing track or comprise a new track. Slant tracks are given time to mature through a track promotion and deletion logic which computes a confidence value for each peak. When a particular track confidence is high enough, then the peak is reported to the operator as a track. Similarly, if a track's confidence is low enough, then that track is deleted from the track table. A sequential detection process provides track life stages which are presented to the operator when a particular track is established. Tracks are further tested sequentially to provide increased confidence while allowing the operator to assess track performance[4]. Tracks continuing to improve in track quality are then promoted to the final tracking stage and passed to the mode-linker for multimode assessment and conversion to ground coordinates. Up to this point all tracks are provided in radar coordinates only. ROTHR forms slant space (radar coordinate) tracks per DIR by using four level sequential testing to build confidence in each newly formed track.

4. At this time tracks may be manually promoted, terminated as well as initiated. However, with hundreds of tracks per DIR this is predominately an automated task.

The promotion levels are known as: Candidate, Potential, Pending, and Verified. The last stage, called Verified, is where each newly verified tracks are tested to determine whether they are a multiple mode of another slant track. They are then transformed to ground coordinates and plotted on the ROTHR geographic display. The ROTHR mode-linker transforms each verified slant track to ground coordinates for the highest power modes available in the coordinate registration tables. The transformed slant tracks are accumulated into families of tracks formed by the application of a central chi-squared statistic to determine whether two track families should be merged. The set of mode structures is maintained for each track family. Association testing considers all admitted (not all modes are available to exist alone) mode combinations present in the CR tables to form each of the family members. This is performed iteratively until the best set of combinations, in the central χ^2 sense is attained. At that time, the linkage is reported.

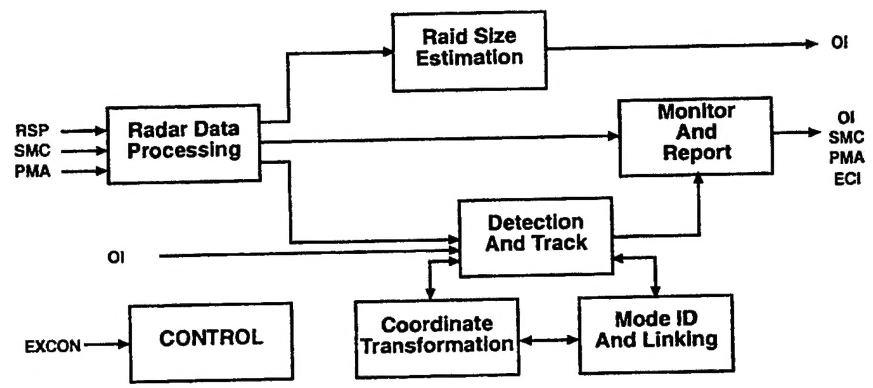


Figure 6. ROTHR Slant Tracker Functional Flow Diagram

The module referred to Detection And Track performs the following sets of functions:

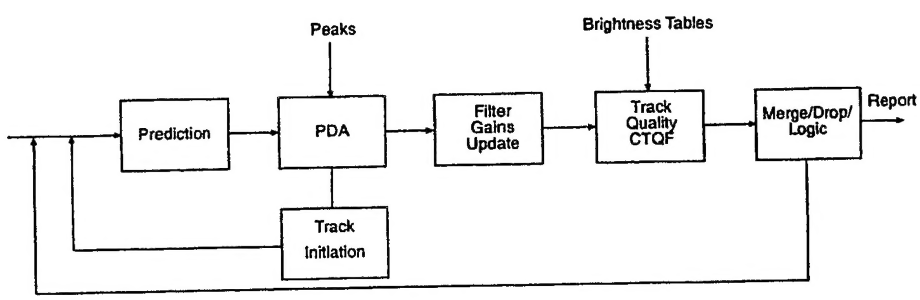


Figure 7. Detection And Track Portion Of ROTHR Slant Tracker

The final stage involving mode-linking produces coordinated converted ground tracks. Ground tracks are a reportable quantity to the end-user community. Mode-linking is a

critical area because potential sources of error involve both the mode linkage decisions and the current ionospheric model.

A collection of simulated slant tracks are presented in Figure 8, where the target Signal to Noise Ratio is color coded using the scale at the bottom of the figure. Since these curves are simulated they represent the best "fit" for a particular model. Unfortunately, tracks rarely look as clean in practice.

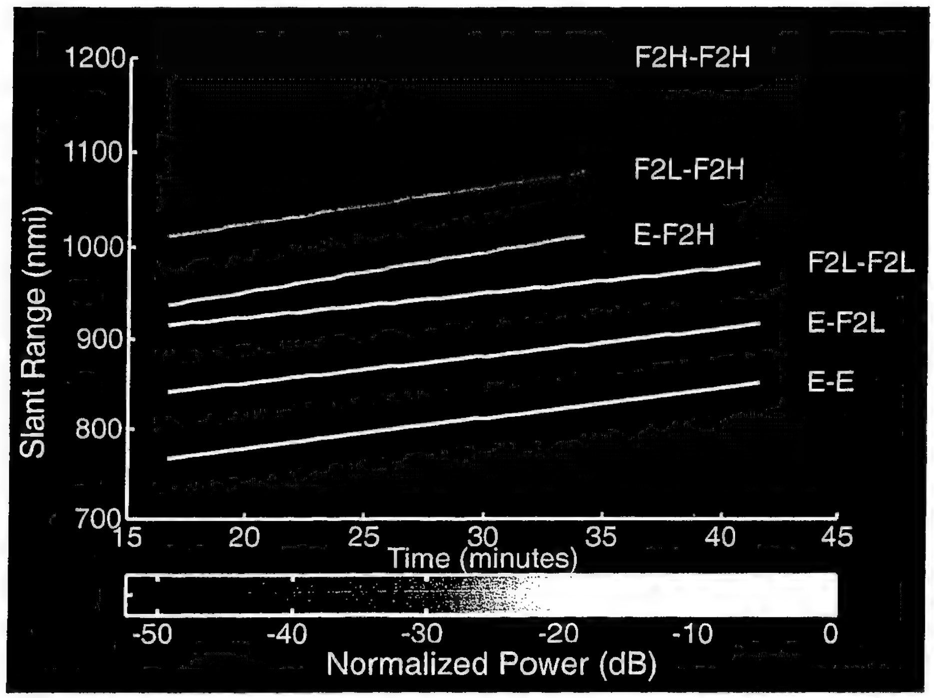
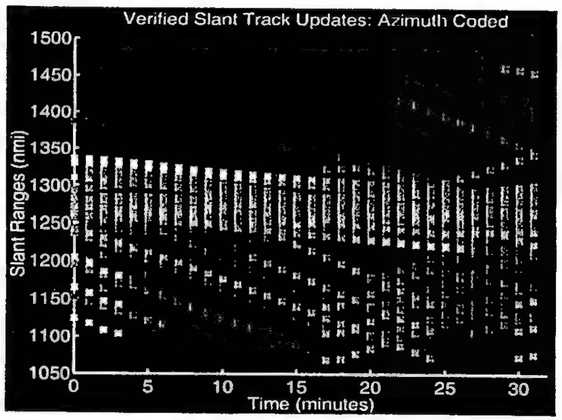
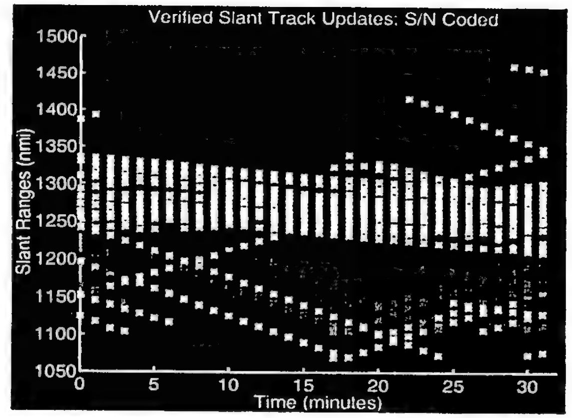


Figure 8. Simulated Multi-Mode Slant Track Output For A Single Target

Simulated data appears here for illustrative purposes and to demonstrate the complexity of the problem in the absence of mis-detections, noise and anomalous ionospheric effects which must all be accounted for in an operational context. The nature of the mode-linking problem is further complicated by overlaying many targets, each containing their own multi-mode variations of the above figure. This is primarily due to the differing ground range dependence of those targets in relation to each other and to possible ionospheric differences between different ground target positions[5]. An example of this complexity appears in Figure 9. In that figure, multi-mode slant track combinations are formed by inversion of ground tracks using coordinate registration tables. Such a

5. It is possible and often frequent that targets in the rear portion of the DIR experience different mode characteristics than targets located in the front portion.





Multi-Mode Slant Track Combinations Formed By Inversion Of Ground Tracks Using Coordinate Registration Tables

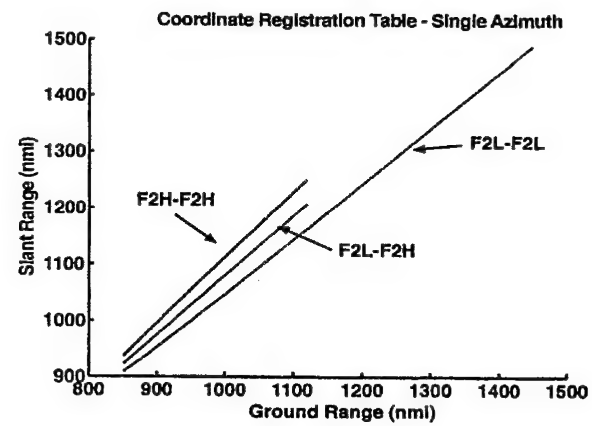


Figure 9. **Simulated Slant Tracks Driven By FAA Ground Truth**

reconstruction of "ideal" slant tracks was invaluable for testing our initial modelinking algorithms in relatively noise-free scenarios.

RELATIVE TARGET POWER

Relative power levels have been used in Figure 8 by employing the following modification of the radar equation,

$$P_r(\mathrm{el},f) = \frac{P_t G_t(\mathrm{el}_t,f_{op})}{\mathrm{WFA}_t}\sigma_{tgt}\frac{A_r(\mathrm{el}_r,f_{op})}{\mathrm{WFA}_r}\frac{1}{L_a} \qquad \text{Equation 5}$$

where the loss due to ray spreading is given by the Wave Front Area (WFA),

$$\mathrm{WFA} = 4\pi r_e \sin\left(\frac{\mathrm{GR}}{r_e}\right)\tan(\mathrm{el})\frac{\partial \mathrm{GR}}{\partial \mathrm{el}} \qquad \text{Equation 6}$$

which contains an inherent "focusing" effect present at the ionospheric "skip" distance and may be manifested as less dominant horizon focusing at the far ground ranges. Unfortunately, this equation is poorly representative of power when compared with measured data. However, it is the currently accepted model for power. Figure 8 consists of power levels normalized to the peak mode. Notice these relative level have characteristic level differences which may be of future use as a sub-mode discriminate if predicated reliably[6]. The envisioned usage would consist of an added piece of information to force a decision in the event of a null condition hypothesis.

SIMULATION FUNCTIONAL FLOW

In order to ascertain truth before neural network development, we created a simulation to assess the details of ionospheric mode-linking in the absence of "real-world" effects. The outputs of this simulation have been utilized in the Figures previously shown. The functional flow of the simulation appears in Figure 10.

6. The current ROTHR mode linker has abandon all but a rudimentary usage of predicted power due to the unreliable nature of the predictive capability inherent in the current technology.

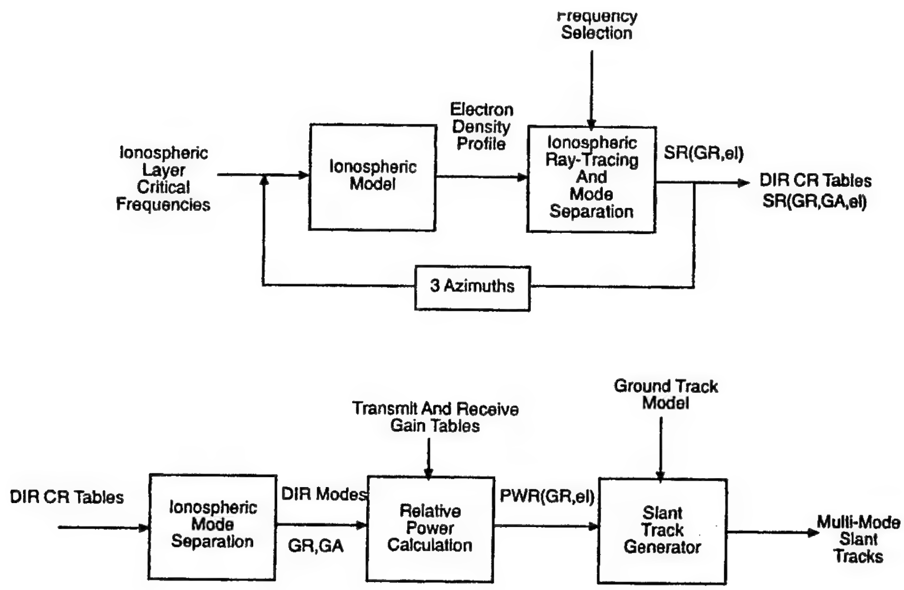


Figure 10. Simulation Functional Flow

The upper portion of the Figure 10 refers to the formulation of the Coordinate Registration Tables on a DIR by DIR basis. Each DIR is divided into three azimuth sectors[7] for use by each DIR. The bottom portion shows the generation of slant tracks by inversion of the Coordinate Registration Tables. Ground tracks are converted to slant coordinates by this procedure. This simplified approach has allowed us to understand the foundation of slant track multi-modes. Additionally, if the "real-world" tracks were similar, within a pre-determined error budget, we could link modes very quickly and with high reliability.

ROTHR COORDINATE REGISTRATION TABLE GENERATION

The ROTHR CRT generation which PMA employs is given by the functional flow shown on the next page. The best match to the ionosphere is obtained with ray-traced results for this ionosphere, for the entire coverage area, forming a table called the Current Ionospheric Model (CIM). The CIM is indexed into for each DIR location to form the Coordinate Registration tables shown to the right.

7. The radar resolves each DIR into $\frac{1}{2}$ degree beams nominal to the radar's mid-band frequent

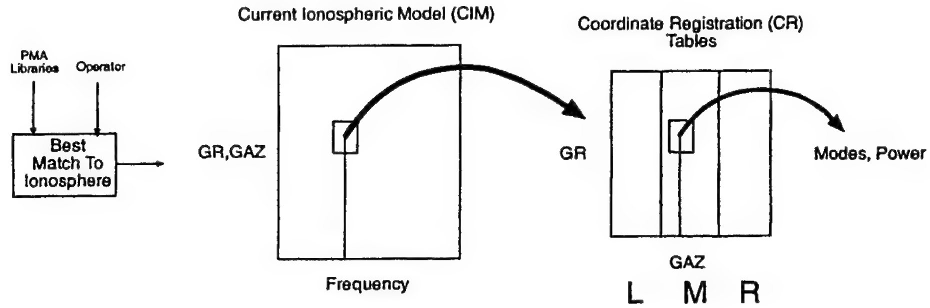


Figure 11. PMA Coordinate Registration Table Generation

The functional flow shown in Figure 11 existed in the ROTHR system at the time of the study. Since that time, ROTHR has integrated Real Time Ray Tracing (RTRT) to improve ground accuracy. The software now generates a CRT for each DIR separately without the need for a Current Ionospheric Model for the entire coverage area. The CRT at the right hand side of this figure is unchanged, but the step in the center is no longer necessary.

RTRT creates ray-tracings for use in mode linking on-the-fly in real-time for each DIR under consideration. This has the substantial advantage of being more closely similar to the observed ionogram used for matching. The former method of pre-computed library ray-tracings suffered from an inherent granularity problem that was not easily overcome without costing more in throughput than it saved. Hence, the library technique is no longer required and with it the Current Ionospheric Model (CIM) as well.

The current mode-linking architecture employs a nearest-neighbor exhaustive search of the available modes in the CR tables. The metric for association is a χ^2 distributed statistic with fixed ionospheric variance values and additive process noise calculated in real-time by the Kalman filter for each slant track admitting association. The association logic of the current ROTHR mode-linker is shown in Figure 12.

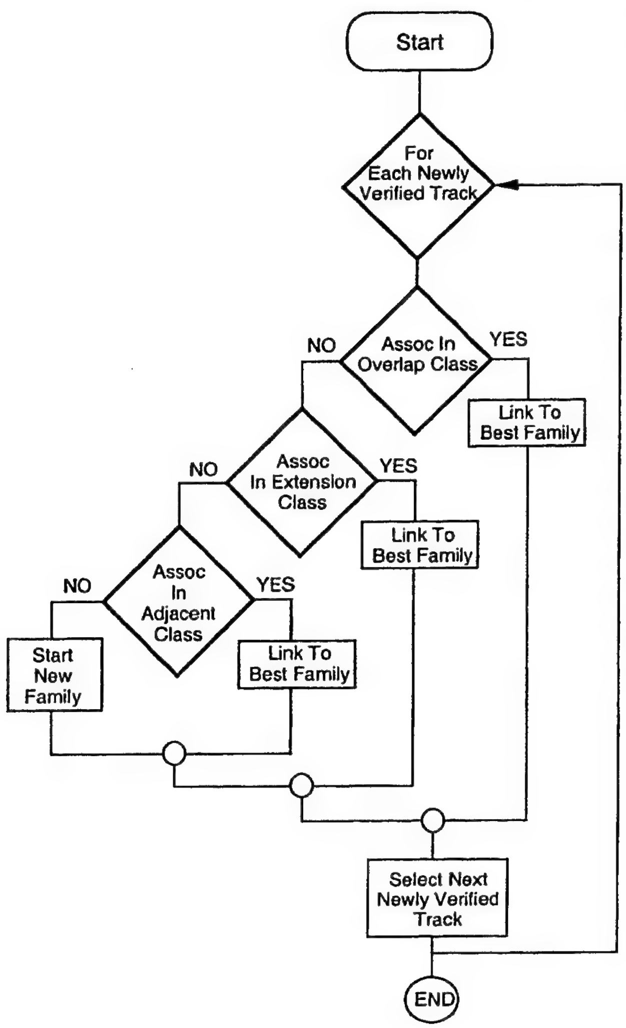


Figure 12. ROTHR Mode-Linker Logic Flow

Association logic may be sub-divided into "macro" classes which involve a DIR dependent class structure and "micro" classes which involve association and classification of slant tracks for ground coordinate conversion. The macro-association classes for intra-DIR classification are described as follows:

1. *Temporal Overlap Associations* - This function provides linking decisions for tracks within a DIR that overlap in the time dimension.
2. *Temporal Extension Associations* - This function provides linking decision for opportunities involving DIR handover.
3. *Temporal Adjacent Associations* - This function provides linking decisions for tracks that involve maneuvers.

The decision logic which determines the Best link to the family occurring in the functional flow is determined by threshold comparison using the χ^2 test as an estimator.

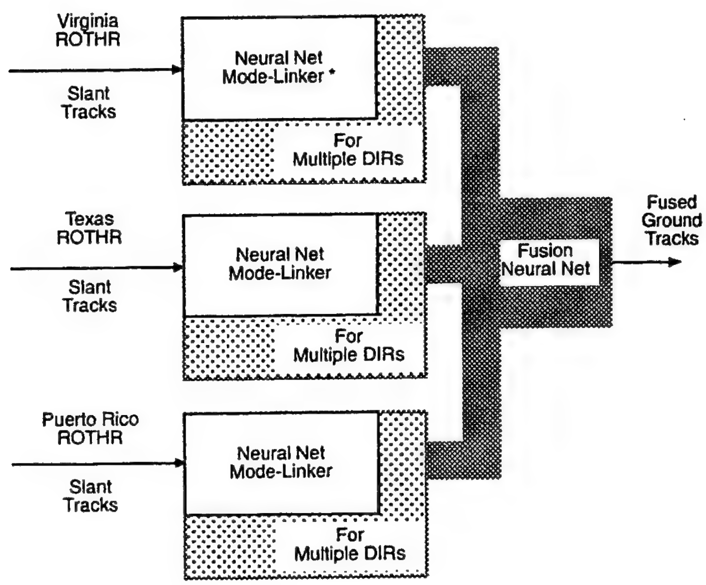


Figure 13. Fusion Neural Network Structure

It is possible to apply similar DIR to DIR macro-association logic using neural networks which act to fuse tracks across DIR boundaries and may provide fusion of radars. This is shown in Figure 13, above. Each boundary contains a neural classifier working on different data characteristics but employing similar technology. The advantage of such a system is the software modularity provided.

This portrays one of the fundamental problems with mode-linking via CRTs. Excursions from a model based ionosphere produce poor "fits" with measured data. The reason is obvious. It is not possible in an operation environment to accept such excursions from the model based ionosphere and often "fits" are forced with erroneous ground ranges.

Compensation for differing models and the real ionosphere forces a growth in the uncertainty for classification. The current ROTHR mode-linker "opens-up" the allowed variance as process induced noise and accommodates errors between the models and observed tracks.The current procedure works, but would benefit from a reduction in the allowed process variance tables. This would improve the probability of falsely associating tracks which do not belong assessed track families.

The goal of the neural network mode linker was to develop an adjustable process noise which would "learn" the uncertainty required by current conditions and employ this appropriately in an automated fashion. Learning to adjust the process noise variance requires a level of adaptation that exceeded this initial study. However, we shall describe the work leading up to this point and elucidate the potential for future work. Developing this approach more fully requires that both potions of the ARTMAP classifier are present. We show here the steps leading to this point and the resulting classification algorithm. This requires half of the ARTMAP classifier but admits the level of adaption required for future development.

IONOSPHERIC MODE-LINKER NEURAL NETWORK

The architecture for using mode-linking employs a combination of neural networks. These consist of Self-Organizing Feature Maps (SOFM) and Adaptive Resonance Theory Maps (ARTMAP). They are designed to interact in a functional fashion. However, the training required is separate for each while their action may be dependent. The SOFM networks are primarily designed to provide a discrimination function while the ARTMAP performs a feature classification function.

Figure 14 provides an architecture for employing neural technology to perform ROTHR's mode-linking function. The flow shows multi-target multi-mode slant tracks as input. They first encounter a SOFM which is designed to separate out tracks belonging to the same target. The SOFM provides discrimination of multiple targets using slant range rate and slant azimuth rate. Sorting multiple targets into separate multi-mode tracks allows the ARTMAP classifier to map these multi-mode members into a distinct ground range. ARTMAP requires ionospheric ray-trace information in the form of the ROTHR CR tables.ARTMAP learns these tables as specifying unique combinations of slant ranges which map to specific ground ranges.

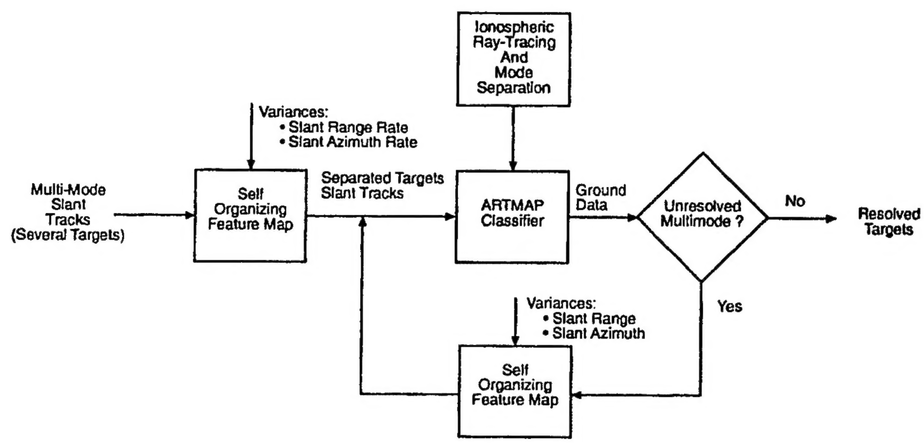


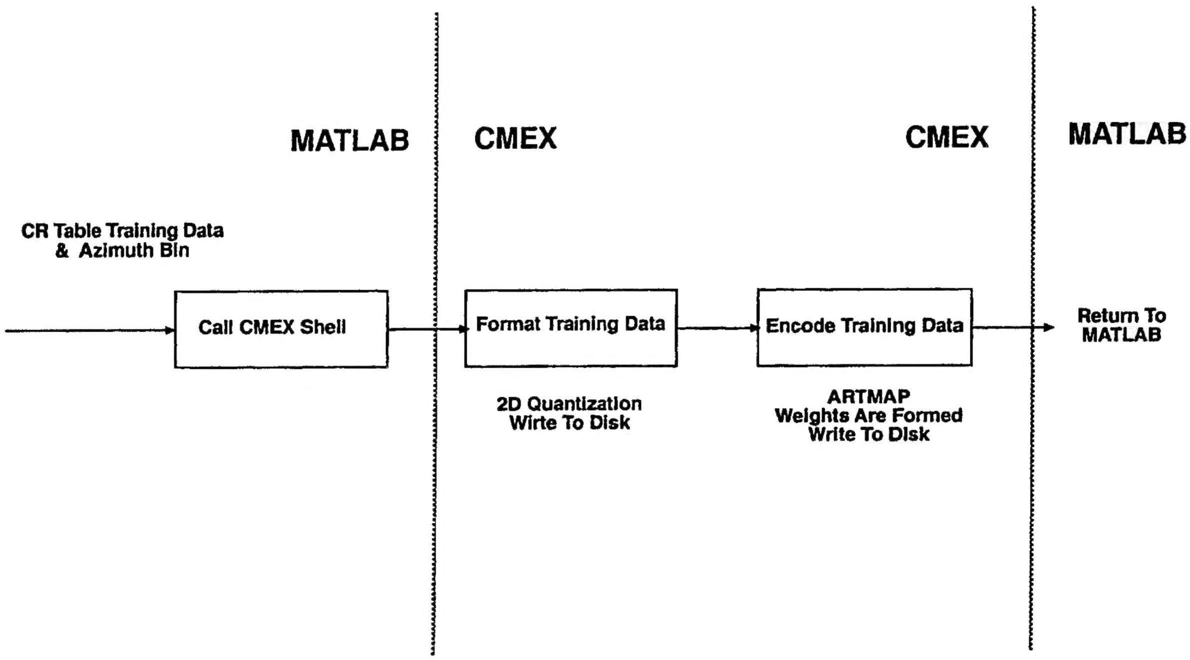
Figure 14. ROTHR Mode-Linker Architecture Using Neural Networks

One difficult problem with OTH radar technology is the mode-linking problem. Tytpically, a table which describes the characteristics of the ionosphere is created using measurements from atmospheric soundings. This coordinate registration (CR) table, maps slant range to ground range coordinates for various layers of the ionosphere. However, there is ambiguity in the table since many times there are multi-modes present at a particular ground range. The aim of the neural network technology is to deal with this ambiguity by computing a closeness of match between CR table and incoming multimodes.

The match metric is computed in a parallel fashion, therefore bypassing restrictions inherent in pair-wise approaches. The demonstrated result is superior mode-linking performance, combined with scalability both in CR table construction and ROTHR tracker abilities.

Neural Network Algorithms

The ROTHR Neural Network Mode-linker is comprised of two neural networks bound by heuristics. In the first network, multi-mode returns are grouped into clusters likely to belong to the same target. Each cluster of returns are then passed along to the second network, which performs the actual mode-linking to ground coordinates. A ground



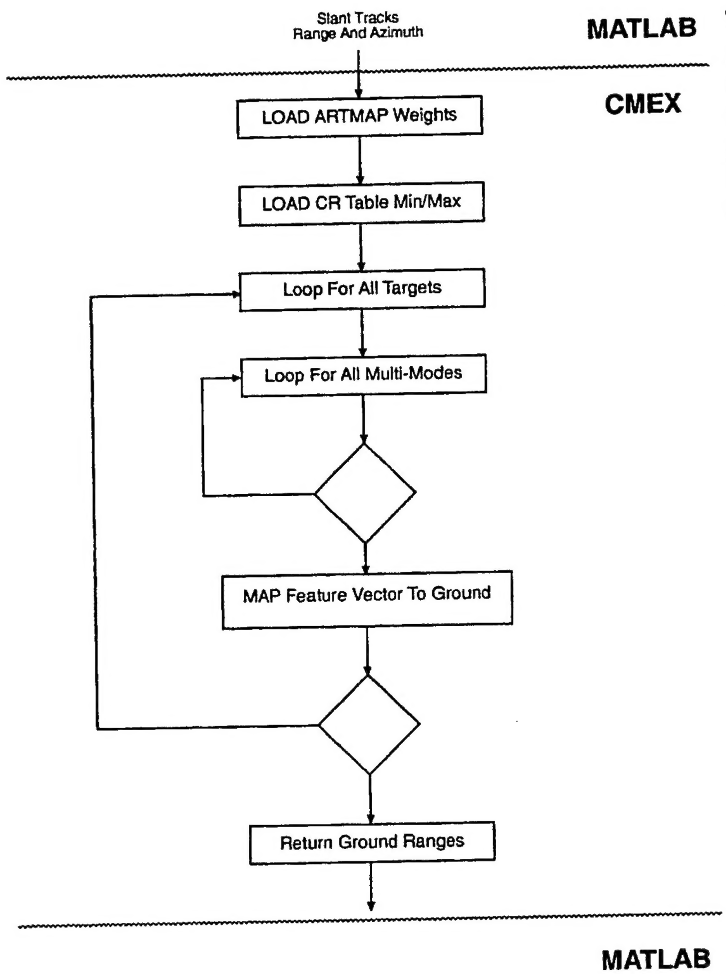
range and azimuth value is assigned to each of the above clusters, or targets.

The first neural network is a self-organizing feature map, or SOFM, which can classify vector inputs based on a Euclidean measure of distance. The network is comprised of a 2-D spatial array of nodes. The dimensions used here are slant range rate (SRR) and slant azimuth rate (SAZR). These coordinates were selected based on our experience with ROTHR data: those multi-modes with similar SRR and SAZR were likely to belong to the same target. The position of each node is determined over the course of training on actual observed data. The resulting distribution of cells can therefore adaptively quantize the space under consideration. In addition, closely spaced nodes will result in areas of the space which are densely populated with observations. However, some cells will remain in the areas where few observations are made. Again, the result is an adaptively tuned representation of all of the SRRs and SAZRs observed by the radar. For a transitional effort, it may be possible to develop a stable map which continues to learn during its operation. However, for this effort, learning was halted once an acceptable distribution was achieved.

The second neural network employs a mapping from slant range to ground range coordinates. The Adaptive Resonance Theory MAP (ARTMAP) algorithm was applied to learn the mapping in the CR table. ARTMAP is a supervised learning algorithm which maps input/output vector pairs presented during learning. An important feature of ARTMAP is its ability to learn the appropriate mapping in a stable fashion after only one pass through the training set. This feature is critical since the CR tables within ROTHR are updated frequently. Once the training of this network is complete, the system is ready to accept slant tracks.

Algorithm Implementation

The ROTHR simulator ('make_tracks') generates slant tracks that are mapped to ground coordinates by the mode-linker. Alternatively, actual ROTHR data, or previously computed slant tracks, can be used to test the mode-linker using another MATLAB program ('mode_link'). A flowchart of the 'mode_link' simulation appears in Figure 15.



The neural network mode-linker is implemented using a combination of 'C' code and Matlab 'M-files'. The 'C' code is called via the built-in 'CMEX' interface to MATLAB. Using such an interface, compiled object code can be directly called by the MATLAB interpreter. The result is a dramatic speed increase with very little overhead penalty. Furthermore, since the key algorithms are already coded in 'C', it will facilitate the transition of the project onto an operational platform.

Figure 15. Neural Network Flow